Attachment 1
Notes and comments supporting the answer to Question 6

1 GST's Experience with Smallsat Missions

GST has been pursuing Smallsat-based designs for the past several years that would serve as lower cost, low-risk alternatives to existing Earth observation designs. Emphasis has been placed on designs that are consistent with existing missions in terms of image geometry and radiometry to insure continuity with existing archives, while dramatically increasing temporal repeat frequency and removing the threat of data gaps. Although GST has placed particular emphasis on developing much lower cost approaches to acquiring a greater volume of Landsat-like passive, optical measurements globally, the application of similar approaches can be applied to other types of Earth observation as well.

A representative example of our in-depth Landsat-specific work can be found in the September 2011 submission of a NASA Ames-sponsored, fully compliant Earth Venture-2 mission concept proposal called TerEDyn, short for the "Terrestrial Ecosystem Dynamics (TerEDyn)" mission. That proposal, led by GST, was a firm fixed price VNIR-SWIR solution (TRL $\geq$ 6) to image more than double the swath width and acquire greater than four times the daily areal coverage as any prior Landsat mission at a cost that fit easily within the $150M EV-2 funding cap. Since that September 2011 submission, our efforts have continued to advance that VNIR-SWIR design and to add thermal infrared (TIR) imaging capability to be more compliant with Landsat 8 measurements. This more up-to-date TerEDyn concept was described in our recent response to NASA's Sustainable Land Imaging Architecture Study RFI; that NASA RFI response is attached to this OSTP RFI response as reference material.

2 Historical Recap of Pecora's Earth Observation Vision

The Earth observation satellite program now known as Landsat was originally envisioned in the mid-1960s by William Pecora and colleagues in the USGS, NASA, universities, and other government agencies to deploy single satellite systems, each with a repeat cycle of 16-18 days, *but with up to four satellites operating at any given time, to provide ~4-day repeat coverage.* Such imaging frequency was considered necessary to achieve clear-view temporal perspectives essential for monitoring Earth surface dynamics in the presence of considerable terrestrial cloud cover.

Cloud contamination is the first order issue in passive optical land imaging. A primary goal for the Landsat program is to "periodically refresh a global archive of Sun-lit, substantially cloud free, land images." *Frequent repeat imaging is critical to achieve this mission.* The desired 4-day temporal repeat goal of the Landsat visionaries has never been achieved; although, in the early 21st century, the fortuitous, simultaneous operation of Landsats 5 and 7 achieved half of the original vision. This 8-day repeat cycle continues today with Landsats 7 and 8, but with Landsat 7 only expected to be operational through 2017 due to fuel limitations. How the visionaries of the program seemed to know back in the mid-1960s that 4-day repeat cycles would be necessary due to cloud cover impacts is still not appreciated. In fact, questions have been posed regularly concerning what repeat frequency is, in fact, needed for successful land imaging.

3 The Impact of Cloud Cover on Earth Observation Success

To address needed Earth observation frequencies in the presence of cloud contamination, Goward, Loboda (Asst. Professor, UMD Geographical Sciences), and Williams recently completed a study of this issue through analysis of 10 years of daily MODIS Terra observations. Their goal in this study was to quantify the probability of acquiring "cloud-free" imagery for selected temporal targets (weekly, biweekly, monthly, seasonally) by employing observatories with variable temporal repeat frequency (daily, 2-day, 4-day, 8-day, 16-day).

MODIS Terra is a lower spatial resolution imager than Landsat but is in a near-simultaneous orbit with Landsat and, in mid-latitudes, achieves near-daily repeat coverage. The region selected for these initial analyses was the eastern U.S. extending from New England to the Midwestern U.S. (**Figure 1**). The analysis examined three Landsat scene equivalents in Maryland, Pennsylvania, and Indiana. This U.S. location is representative of humid, mid-latitude locations where agriculture and forestry land use practices dominate. A "substantially cloud-free image" is defined as a composited image over a specified period of observations (weekly, biweekly, monthly, seasonally) with <10% cloud contamination.

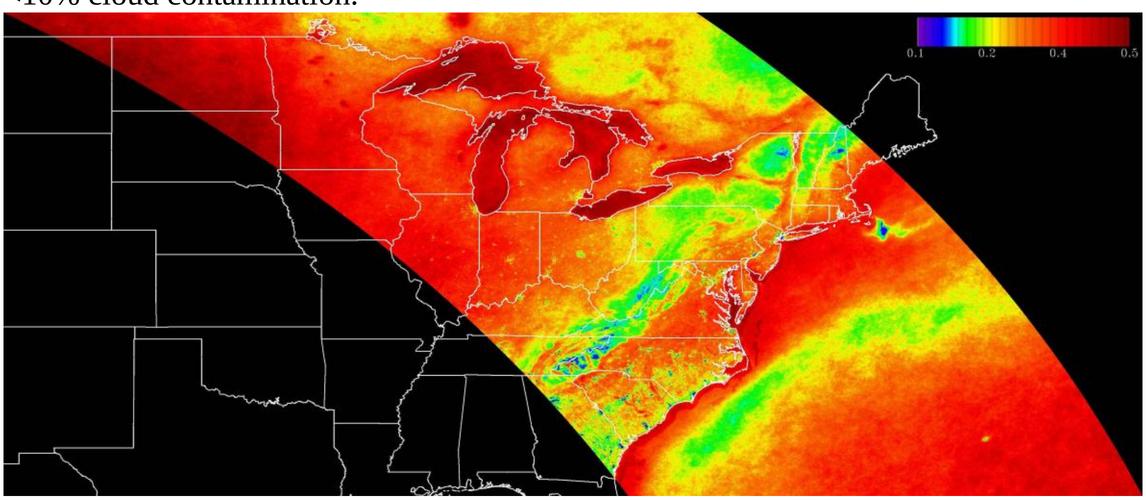

Figure 1 – Probability of Cloud-Cleared Views for the Summer "Season" (June, July, and August) for Eastern U.S., summarized from a 10-Year MODIS Daily Observation Record

Locations where the probabilities are higher are noted is shades of oranges and reds (30% and greater). Lower probability areas are noted in yellows, greens, and blue (<30% probability). Note the high probability of encountering clouds in mountainous regions, including the Appalachians, Adirondacks, Green, and White Mountains. The Great Lakes water bodies are relatively cloud-free along with western Illinois, eastern Iowa, southern Minnesota, and into the Dakotas.

Their study results demonstrate that:

- Daily imaging is necessary to produce a weekly cloud-cleared observation;
- 2-day repeat imaging will yield, on average, a biweekly cloud-cleared product;
- 4-day repeat imaging produces monthly cloud-cleared images;
- 8-day imaging, as we have with two Landsats in phased orbit, yields a seasonal cloud-cleared view; and
- 16-day repeat coverage, provided via one Landsat, can be expected to yield a cloud-cleared look only once per year.

***The simple conclusion is that increased temporal repeat frequency is a critical requirement to meet the goals of most Earth observation programs*.** Therefore, it is important to note that the historical approach of serially building and launching one satellite at a time does not support the critical science objectives and operational missions that require weekly or better clear-surface observations. **A truly sustainable, operational system capable of producing at least biweekly clear-surface observations requires a larger number of satellites in orbit with replacements in the pipeline.** Current Landsat satellites, for example, are prohibitively expensive to achieve this goal; therefore, lower cost smallsat-based Landsat-like missions must be pursued. In addition, the successful development of lower cost small satellites will lead to a multi-satellite solution that can easily adapt to changes in technologies as they mature while simultaneously minimizing the ongoing threat of a crippling data gap.

4 The Terrestrial Ecosystem Dynamics (TerEDyn) Mission Concept

For over three years, GST has led a group of experts that has been actively researching and developing a much lower cost, small satellite-based, moderate resolution, land imaging concept designed to acquire data consistent with Landsat missions in terms of acquisition geometry, areal coverage, spectral, spatial and radiometric characteristics, and calibration that will blend seamlessly with the baseline Landsat archive. The initial solution was fully articulated in the "Terrestrial Ecosystem Dynamics (TerEDyn)" flight mission concept proposal submitted to NASA on September 2011, in response to the Earth Venture-2 (EV-2) AO.

The TerEDyn concept (patent pending) is an innovative approach, driven by a science requirements process (see Appendix A), to acquire passive optical, multispectral imagery (Landsat OLI bands 2 – 6, including SWIR1) using a push-broom sensor carried on a smallsat platform that has significant flight heritage. The TerEDyn imager is designed to image a 400 km swath yielding global land coverage after 7 days and to be operated in an "always ON, imaging when over Sun-lit land" mode. The combination of a greater than double swath width and much more robust imaging duty cycle would result in the capture of more than four times the areal coverage collected by any prior individual Landsat satellite. TerEDyn would support studies of vegetation dynamics and food security at an individual field scale via global collection of wall-to-wall 15 m VNIR and 30 m SWIR imagery.

TerEDyn takes advantage of evolving small satellite and data handling/processing technologies to collect and assess these robust data sets at costs that are reasonable and sustainable. This concept puts TerEDyn at a lower orbital altitude than Landsat 8 to take advantage of frequent under flights throughout its mission life for cross calibration purposes. *Implementation of the TerEDyn concept is low risk because it draws heavily from both hardware and software lessons learned via NASA's historical scientific oversight of missions such as Landsat, AVHRR, SeaWIFS, and EOS MODIS as well as Surrey Satellite Technology's development and oversight of their Disaster Monitoring Constellation (DMC) capabilities*. Because the TerEDyn end-to-end solution is designed to acquire imagery that will blend seamlessly with observations already held in the 41-year Landsat archive, it also offers significant enhancements for scientific, humanitarian, strategic, and commercial applications.

The content of the EV-2 TerEDyn proposal, which includes detailed breakout of cost* elements and foldout drawings, is a valuable reference document relevant to this RFI exercise. Reviewers of this RFI are encouraged to contact either NASA HQ or GST to get a copy of that EV-2 proposal for use as a reference document.

5 The Science Traceability Matrix

<table>
<tr><th rowspan="2">Science Goals (NASA SSE Roadmap 2010) Carbon Cycle and Ecosystem</th><th rowspan="2">Science Objectives</th><th colspan="2">Scientific Measurement Requirements</th><th rowspan="2">Instrument Functional Requirement</th><th rowspan="2">Projected Performance</th><th rowspan="2">Mission Functional Requirements (Top Level)</th></tr>
<tr><th>Observables</th><th>Physical Parameters</th></tr>
<tr><td rowspan="2">Document and understand how terrestrial ecosystems are changing as they are affected by humans</td><td>1. Quantify Terrestrial Productivity</td><td>Temporal vectors (30-day time step) of : Surface (VNIRS) Spectral Reflectance NDVI = (NIR-Red)/(NIR+Red)
Pigment Index (Green - Red)/(Green+Red)
Structural Index (SWIR-NIR)/(SWIR+NIR)
Surface Temperature (split window)</td><td>Fractional Absorbed Photosynthetically Active radiation
(fAPAR) = NDVI
fAPAR used in photosynthesis = Pigment Index
Plant wood structure = SI =(NIR-SWIR)/ NIR+SWIR) plus SWIR and NIR
Surface Temperature (split window)</td><td>Spectral Bands (µm)
Green 0.53 - 0.60
Red 0.63 - 0.68
NIR 0.85 - 0.89
SWIR 1.56-1.66
TIR1 10.3-11.3
TIR2 11.5-12.5</td><td>Spectral Bands (µm)
Green 0.53 - 0.60
Red 0.63 - 0.68
NIR 0.85 - 0.89
SWIR 1.56-1.66
TIR1 10.3-11.3
TIR2 11.5-12.5</td><td rowspan="2">• Inclination 98°
• Altitude 615 km
• Repeat Frequency 8 –days Station Keeping ±20 km Acquisitions - always “ON,” imaging over Sun-lit land
• Equatorial Crossing 9:45 AM local
• Years of Operations: At least Two years plus Commissioning
• Expected to last 5+ years.</td></tr>
<tr><td>1a. Establish Land Cover Dynamics</td><td>30-day cloud-free composites Surface spectral reflectance
• Blue - 0.45- 0.52
• Green - 0.53 - 0.60
• Red - 0.63 - 0.68
• NIR - 0.85 - 0.89
• SWIR - 1.56-1.66
• Surface Temperature</td><td>• TOA spectral reflectance from solar constant and sensor relative spectral response (RSR) function Atmospheric scatter from combined blue and red spectral measurements
• Atmospheric absorption avoided with narrow band passes
• Cloud-clearing achieved through TIR Cloud/Shadow ID and compositing 4 acquisitions per month
• Surface spectral reflectance from above steps</td><td>Spectral Bands (µm)
Blue 0.45- 0.52
Green 0.53 - 0.60
Red 0.63 - 0.68
NIR 0.85 - 0.89
SWIR 1.56 - 1.66
SNR > 50 Swath - >400 km
IFOV < 50 m VNIRS, <100 m TIR
Precision 0.5% TOA Reflectance
Acc 1.0% Surf Reflectance
TIR1 10.3-11.3
TIR2 11.5-12.5
IR Precision 0.5°C,Acc. 1.0°</td><td>Spectral Bands (µm)
Blue 0.45 - 0.52
Green 0.53 - 0.60
Red 063 - 0.68
NIR 0.85 - 0.89
SWIR 1.56 - 1.66
SNR > 90 in all bands Swath – 400 km IFOV – 30 m (VNIRS)
IOFV – 100 m (TIR)
Precision 0.5% TOA reflectance
Accuracy 1.0% Surf. reflectance
TIR1 10.3-11.3
TIR2 11.5-12.5
IR Precision 0.5°C, Acc. 1.0 °</td></tr>
</table>

Science Goals (NASA SSE Roadmap 2010) Carbon Cycle and Ecosystem	Science Objectives	Scientific Measurement Requirements: Observables	Scientific Measurement Requirements: Physical Parameters	Instrument Functional Requirement	Projected Performance	Mission Functional Requirements (Top Level)
	1b. Leaf Area Index	Temporal vectors (30-day time step) of: • Surface (VNIRS) Spectral Reflectance • Principal Components Spectral signatures	Land Cover (general categories): forest; cropland; grasslands; urban/settled areas; fraction of trees, shrub, and grass cover; barren lands; persistent snow; water bodies	Spectral surface reflectance(ΔSR)/month better than 2% in Green, Red, NIR and SWIR	SR/month better than 1% in Green, Red, NIR and SWIR	
	2. Global Productivity Allocation	Global NPP Analysis Global Land Cover Map	Relationship between Land Cover Type and NPP	See Objectives 1 and 1a	See Objectives 1 and 1a	
	2a. Forest Dynamics and Product Allocation	2+ years of forest land cover analysis Forest NPP analysis	Inter-annual forest disturbance	Growing Season surface spectral reflectance measurements • Spectral Bands (μm) Green 0.53 - 0.60 • Red 0.63 - 0.68 • NIR 0.85 - 0.89 • SWIR 1.56 - 1.66	Spectral Bands (μm) Green 0.53 - 0.60 Red 0.63 - 0.68 NIR 0.85 - 0.89 SWIR 1.56 - 1.66	
	2b. Global Agricultural Production Allocation	Surface VNIRS Spectral Reflectance NDVI/TIR Principal Components Spectral signatures Crop NPP analysis	Detailed annual global crop-type maps: corn, soybeans, winter wheat, summer wheat, rice, sorghum, etc.	Spectral surface reflectance (SR)/month better than 2% in Green, Red, NIR, and SWIR 1°K Surface Temperature	SR/month better than 1% in Green, Red, NIR, and SWIR 1°K Surface Temperature	
	2c. Ecosystems Reserves Allocation	Global NPP Analysis	Overlay of global natural reserves	See Objective 1	See Objective 1	
	3. Climate Data Record Definition	Review of TerEDyn products and progress	Scientific definition of land biospheric dynamics data record	Assessment of TerEDyn results looking forward to future land remotely sensed measurements	Summary of TerEDyn results	